

PROCESS FOR THE CATALYTIC PARTIAL OXIDATION OF H₂S USING STAGED ADDITION OF OXYGEN

BACKGROUND OF THE INVENTION

Technical Field of the Invention

[0001] The present invention generally relates to sulfur recovery processes and to apparatus for removing sulfur from H₂S-containing gas streams and producing elemental sulfur. More particularly, the invention relates to H₂S catalytic partial oxidation processes that include staged addition of oxygen, and to apparatus for carrying out such processes.

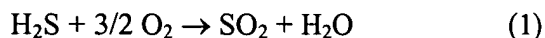
Description of the Related Art

[0002] Sulfur removal from H₂S-containing gas streams is a field of endeavor that is receiving a great deal of attention today, particularly in the petroleum industry. Considerable quantities of H₂S are created from the refining of petroleum in processes such as crude oil hydrodesulfurization, gasification of coal and desulfurization of natural gas. The removal of sulfur from natural gas is a particular concern because utilization of the enormous supply of natural gas existing in underground reservoirs all over the world is hindered due to the presence of naturally-occurring H₂S along with the methane and other light hydrocarbons that make up natural gas. Some natural gas formations contain only a relatively small concentration of H₂S, yet even those types of natural gas wells typically remain shut-in today because the cost of removal of the H₂S using existing methods and apparatus exceeds the market value of the gas. A further deterrent to full utilization of H₂S-containing natural gas resources is the corrosive effect of the H₂S component of liquefied natural gas on the transportation pipes and storage vessels that are needed to bring the H₂S-containing natural gas from remote locations to existing sulfur treatment plants.

[0003] The removal of sulfur from naturally occurring and industrially produced H₂S-containing gas streams is necessitated by the high demand for clean energy sources, and by increasingly stringent clean air standards for industrial emissions that restrict or prohibit the release of H₂S into the environment due to its high toxicity and foul odor. Since the amount of sulfur recovered from an industrial H₂S-containing stream may be quite large, the elemental sulfur product can have significant commercial value.

[0004] Many processes have been described for accomplishing the removal and recovery of sulfur from H₂S-containing gases. The sulfur plants in common use today employ a modification of a process that was developed over 200 years ago in which H₂S was reacted over a catalyst with air (oxygen) to form elemental sulfur and water (the Claus process). Sulfur recovery was low and the

highly exothermic reaction was difficult to control. Modified Claus processes were introduced to overcome the deficiencies of the original Claus process, and today are generally referred to as "Claus Processes." In a conventional Claus process, the H₂S-containing gas stream is contacted with air or a mixture of oxygen and air in a flame. One third (1/3) of the H₂S is burned according to the equation:



The remaining 2/3 of the H₂S is converted to sulfur via the (Claus) reaction:



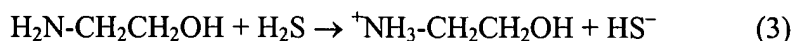
[0005] ($x = 2, 6, \text{ or } 8$ depending on temperature and pressure). The gases are cooled in a fire tube boiler after the burner. Typically, this step converts 55 to 70% of the H₂S to elemental sulfur. The equilibrium of the reaction of equation (2), referred to as the "Claus reaction," limits the conversion. To improve the yield, elemental sulfur is condensed from the gas stream. After sulfur condensation and separation from the liquid sulfur, the unreacted gases are heated to the desired temperature, passed over a catalyst that promotes the Claus reaction, and cooled again to condense and separate the sulfur. Generally, two to three stages of Claus reheater, reactor, and condenser stages are employed. Over the years, most of the modifications to the Claus process have involved improvement of burner design, use of more active and durable catalysts, and use of different types of reheaters. Anywhere from 90 to 98% of the H₂S fed to the unit is recovered as elemental sulfur. Any remaining H₂S, SO₂, sulfur, or other sulfur compounds in the Claus plant effluent are either incinerated to SO₂ and discharged to the atmosphere, or incinerated to SO₂ and absorbed by chemical reaction, or converted by hydrogen to H₂S and recycled or absorbed by an alkanolamine solution. This is accomplished by various Claus "tail gas" treatment units, which improve the efficiency of sulfur removal from the gas discharged to the atmosphere.

[0006] Claus processes are generally efficient for processing large quantities of gases containing a high concentration (i.e., > 40 vol. %) H₂S in plants producing more than 100,000 tons of sulfur per year. The Claus-type processes are not suitable for use in cleaning up hydrogen or light hydrocarbon gases (such as natural gas) that contain H₂S, however. Not only is the hydrocarbon content lost in the initial thermal combustion step of the Claus process, but carbon, carbonyl sulfide and carbon disulfide byproducts cause catalyst fouling and dark sulfur. Moreover, carbonyl sulfide is difficult to convert to elemental sulfur. In the past, others have usually addressed the problem of purifying hydrogen sulfide contaminated hydrogen or gaseous light hydrocarbon resources by employing an initial amine extraction technique.

[0007] Typically, alkanolamine absorption of the H₂S component of a gas stream is performed, followed by H₂S regeneration and conventional multistage Claus sulfur recovery, usually including tail gas treatments. According to conventional industrial practices, a hydrocarbon or hydrogen containing gas stream containing a low concentration of H₂S is contacted with a water solution containing an alkanolamine. Alkanolamines commonly employed in the industry are monoethanolamine (MEA), diethanolamine (DEA), methyldiethanol amine (MDEA), diglycolamine (DGA), and diisopropanolamine (DIPA). These are basic nitrogen compounds. The basic alkanolamine reacts with the H₂S and other gases that form acids when dissolved in water to form alkanolamine salts, according to the following generic reaction:



When ethanolamine is the basic alkanolamine, the reaction is:



The hydrogen or hydrocarbon gas, substantially freed of H₂S, is recovered and may be used as fuel or routed to another system for processing. After absorbing the H₂S from the gas, the alkanolamine solution is transported, heated, and placed in a stripping tower. Steam generated from boiling the alkanolamine solution at the bottom of the stripping tower, lowers the vapor pressure of the acid gas above the solution, reversing the equilibrium of the acid gas/alkanolamine reaction described above. The acid gases leaving the stripper are cooled to condense most of the remaining steam. The acid gas stream then goes to a Claus sulfur recovery plant, as described above.

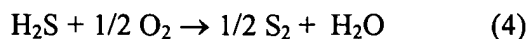
[0008] The major problem with the Claus process is the inherent equilibrium constraint of the Claus reaction caused by the necessity of generating the SO₂ intermediate. Others have addressed this problem by attempting to directly oxidize H₂S to sulfur using alumina based catalysts and low temperature operating conditions. SUPERCLAUS™ processes such as the STRETFORD™ process are examples of low temperature direct oxidation methods. Typically, these processes are catalytic oxidations operating at temperatures below about 454°C, so that the reaction can be contained in ordinary carbon steel vessels. Usually these catalytic oxidation processes are limited to Claus tail gas operations or sulfur recovery from streams that have very low H₂S content (i.e., about 1-3%). One reason for this limited use is that the heat evolved from the oxidation of a concentrated stream of H₂S would drive the reaction temperatures well above 454°C requiring refractory lined vessels such as the conventional Claus thermal reactor. Low concentration H₂S streams will not produce enough energy release from oxidation to sustain a flame as in a thermal reactor stage. The existing catalytic oxidation technologies are thus limited to low concentration H₂S-containing streams using

non-refractory lined vessels. Existing processes are also limited in the amount of sulfur that can be handled because the heat transfer equipment needed to remove the heat of reaction becomes extremely large due to the low temperature differential between the process and the coolant streams.

[0009] Some techniques for improving efficiency of sulfur removal that have been described in the literature for purifying hydrogen sulfide contaminated hydrogen or gaseous light hydrocarbon resources include: 1) adsorbing sulfur cooled below the freezing point on a solid material followed by releasing the trapped sulfur as a liquid by heating the solid adsorbent; 2) selectively oxidizing the remaining H_2S to sulfur using air; and 3) selectively oxidizing the H_2S to sulfur employing aqueous redox chemistry utilizing chelated iron salts or nitrite salts. According to the latter methods, the H_2S -contaminated hydrogen or hydrocarbon stream is contacted directly with the redox reagent such as chelated iron (III) ions. The iron (III) is reduced to iron (II) ion while the H_2S is converted to elemental sulfur. The sulfur in liquid form is separated from the solution. These types of desulfurization units have been shown to be practical when the amount of sulfur to be removed from the stream is below 5 long tons per day. The SULFUROXTM and LO-CATTM processes are examples of this type of H_2S conversion process. Some of these direct oxidation processes use a liquid medium to carry out the oxidation or to act as a carrier for the oxidizer. These processes are also limited in the amount of sulfur recovered due to the heat removal constraints at low temperatures and the need to maintain low temperatures to keep the liquid from boiling. For at least these reasons, existing direct oxidation processes have not proved to be viable substitutes for the Claus process in most industrial applications.

[0010] U.S. Patent No. 5,700,440, U.S. Patent No. 5,807,410 and U.S. Patent No. 5,897,850 describe some of the limitations of existing tail gas treatment (TGT) processes and the difficulty of meeting increasingly stringent government requirements for desulfurization efficiency in the industry. J.B. Hyne (*Oil and Gas Journal* Aug. 28, 1972: 64:78) gives an overview of available processes for effluent gas stream desulfurization and discusses economical and environmental considerations. R.H. Hass et al. (*Hydrocarbon Processing* May 1981:104-107) describe the BSR/SelectoxTM process for conversion of residual sulfur in Claus tail gas or for pre-Claus treatment of a gas stream. K-T Li et al. (*Ind. Eng. Chem. Res.* 36:1480-1484 (1997)) describe the SuperClausTM TGT system which uses vanadium antimonate catalysts to catalyze the selective oxidation of hydrogen sulfide to elemental sulfur.

[0011] U.S. Patent No. 5,603,913 describes several oxide catalysts that have been suggested for catalyzing the reaction



Because reaction (4) is not a thermodynamically reversible reaction, direct oxidation techniques offer potentially higher levels of conversion than is typically obtainable with thermal and catalytic oxidation of H_2S . As mentioned above, conventional direct oxidation methods are applicable to sour gas streams containing relatively small amounts of H_2S and large amounts of hydrocarbons, but are not particularly well suited for handling more concentrated acid gas streams from refineries. For this reason direct oxidation methods have been generally limited to use as tail gas treatments only, and have not found general industrial applicability for first stage sulfur removal systems from gases containing large quantities of H_2S .

[0012] U.S. Patent No. 6,372,193 (Ledoux et al.) describes a process for catalytically oxidizing a gas stream containing a low concentration (up to 25 vol.%) H_2S directly to sulfur over a catalytically active phase carried on a silicon carbide-based support. The catalytically active phase is an oxysulfide of Fe, Cu, Ni, Co, Cr, Mo or W.

[0013] Even though the Claus process still finds widespread industrial use today for recovering elemental sulfur from H_2S that is generated in many industrial processes, such as petroleum refinery processes, and for reducing sulfur emissions from refineries, the Claus process is generally viewed as relatively costly for routine use on a commercial scale. As a result, the Claus process is currently performed mainly for the purpose of complying with government mandated environmental air quality standards. Most of the existing alternative desulfurization processes and systems must resort to use of a number of additional pre-treatments or post-treatment catalytic stages and tail gas treatment units (TGTUs) in order to adequately clean the waste gas that is vented into the air sufficiently to meet current environmental regulations for venting of cleaned H_2S -containing gas streams. Multi-stage tail gas treating units (TGTUs) typically convert the H_2S that did not react in the Claus unit to elemental sulfur by (a) oxidizing completely to SO_2 , (b) reacting the SO_2 with H_2S in smaller concentrations to form elemental sulfur (S^0), and (c) reacting very small concentrations of H_2S with oxygen to form S^0 at low temperatures using a catalyst. A number of TGTUs are usually needed to achieve the 99+% conversion of H_2S to S^0 , and involves a large initial investment and appreciable maintenance costs.

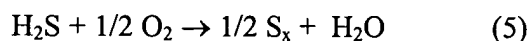
[0014] Significant capital and maintenance costs are associated with conventional multi-stage treatment units. More economical and efficient ways of recovering elemental sulfur from an H_2S -containing gas stream and of removing environmentally harmful H_2S from industrial vent stack

exhaust gases are needed. Conventional desulfurization operations are also not practical for use at small operations such as remote well sites or on natural gas producing off shore oil platforms.

[0015] The basic SPOC™ technology, as described in co-pending, co-owned U.S. Patent Application Nos. 09/625,710, 10/024,679 (US 2002/0134706) and 10/024,167 (US 2002/0131928), which are hereby incorporated herein by reference, provides an alternative to the conventional Claus process to handle H₂S-containing fluid streams. U.S. Patent Application Publication Nos. 2002/0134706 and 2002/0131928 (Keller et al.) describes a method of selectively converting even high concentrations of hydrogen sulfide in H₂S-containing gas streams to elemental sulfur via a short contact time catalytic partial oxidation process (SPOC™) that is more economic and efficient than a Claus type process. The process is carried out in a more compact system than a conventional Claus plant. Conversion of H₂S to elemental sulfur by the SPOC™ process may be accompanied by the formation of some SO₂ as a result of gas-phase reactions between S⁰ and O₂ that occur both downstream from the catalyst zone and within the catalyst zone. This secondary production of SO₂ is typically observed when higher than stoichiometric O₂/H₂S ratios are used to increase the H₂S conversion. An apparatus and process that further improve the conversion of H₂S to elemental sulfur would be valuable in the art, particularly for meeting stringent Federal environmental standards and the demands for cleaner industrial waste gas emissions as required by the Environmental Protection Agency.

BRIEF SUMMARY OF PREFERRED EMBODIMENTS

[0016] The present invention provides a process and apparatus in which H₂S-containing streams, with H₂S concentrations ranging from very low to high (*e.g.*, about 1% to 100% (by volume)), are converted to elemental sulfur and water. The basic SPOC™ process has been modified to improve the total H₂S conversion and the amount of S⁰ recovered. The improvement includes staged air, oxygen or oxygen-enhanced air addition to the reactor whereby the amount of oxygen added to the front of the catalyst bed is such that SO₂ formation is minimized, preferably, no more than 10% of the sulfur in the feed is converted to SO₂. Since this also limits the H₂S conversion, the oxygen is added along the catalyst bed in smaller than stoichiometric oxygen/H₂S ratios to achieve higher overall H₂S conversion and S⁰ yields, and lower SO₂ yields. The reactor is still operated in short contact time mode (*i.e.*, 200 milliseconds or less). H₂S is converted to S⁰ by the catalytic partial oxidation of H₂S according to the reaction



(wherein $x = 2, 6$ or 8 , depending on temperature and pressure). The total or nearly complete conversion of the H_2S component to elemental sulfur is achieved, and the yield of recovered elemental sulfur is thereby enhanced. Since complete oxidation to SO_2 also increases the reaction temperature, staged oxygen addition at sub-stoichiometric oxygen/ H_2S ratios will help minimize the undesired reactions occurring as a result of high temperatures. Also, it is possible to reduce the total amount of oxygen used in the process without making any other changes to the catalyst composition or overall process.

[0017] The new staged air/oxygen catalytic partial oxidation process and system (termed SPOC-IIITM) offers significant advantages for more efficiently recovering elemental sulfur from H_2S -containing streams and for reducing pollution of the air by H_2S from natural gas wells or emissions from petroleum refinery vent stacks, compared to conventional sulfur recovery systems. Another advantage of the present apparatus and process is that it is possible to make a relatively compact sulfur removal plant. The new apparatus and process also make it more economically and environmentally feasible for refineries to utilize high sulfur crude oils by providing for the efficient recovery of sulfur from the accompanying H_2S waste gas.

[0018] Employing a short contact time reactor and a suitable catalyst, the process allows the direct oxidation of H_2S to take place on gas streams containing a much wider range of H_2S concentrations than is presently possible with conventional H_2S direct oxidation processes and operating at temperatures ranging up to about $1,500^\circ\text{C}$. In accordance with one aspect of the present invention, a multistage catalytic partial oxidation process for recovering elemental sulfur from a H_2S -containing gas stream is provided. In certain embodiments, the process comprises contacting the H_2S -containing gas stream with a catalyst that is active for catalyzing the partial oxidation of H_2S in the presence of oxygen to form S^0 and H_2O , the catalyst comprising multiple catalytic regions. This process also includes providing the total stoichiometric amount of oxygen required for the catalytic partial oxidation of the H_2S in the H_2S -containing gas stream to S^0 and H_2O in at least two increments, respectively, to at least two of the catalyst regions, such that a product gas mixture is formed comprising S^0 and H_2O . Preferably, overall selectivity for SO_2 product is no more than 10%, more preferably the production of incidental SO_2 is restricted to less than 5% of the sulfur content of the starting H_2S feed. Elemental sulfur is condensed from the product gas mixture.

[0019] In certain embodiments, the sulfur recovery process includes a first stage comprising contacting a first feed gas stream comprising a mixture of H_2S and an initial incremental of an O_2 -containing gas with a first catalyst portion. The catalyst bed comprises multiple catalyst portions and

has activity for catalyzing the partial oxidation of H_2S to elemental sulfur and water. As a result of such contacting, a first stage product gas mixture is formed. The initial incremental amount of O_2 -containing gas contains less than the stoichiometric amount of O_2 in reaction 5, above, to convert all of the H_2S in the first feed gas stream. In the first stage of the process a first stage product gas stream comprising elemental sulfur, steam and unreacted hydrogen sulfide is produced. Following the first stage of the process is a second stage that comprises contacting the first stage product gas stream with a second catalyst portion, and combining a second amount or increment of O_2 -containing gas with the first stage product gas stream. The second incremental amount of O_2 -containing gas preferably contains less than the stoichiometric amount of O_2 in the reaction to convert all of the unreacted H_2S from the first stage product gas stream to S^0 and H_2O , whereby a second stage product gas stream comprising S^0 , H_2O and unreacted H_2S is created. In some embodiments the process also includes a third stage in which a third incremental amount of O_2 -containing gas is combined with the second stage product gas stream. The third incremental amount of O_2 -containing gas contains less than the stoichiometric amount of O_2 in the reaction to convert all of the unreacted H_2S in the second stage product gas stream to S^0 and H_2O . From this third stage of the process a third stage product gas stream comprising S^0 , H_2O and unreacted H_2S is obtained.

[0020] In some embodiments of the process the concentration of O_2 in the initial feed gas mixture and the amount of O_2 provided in the second incremental amount of O_2 -containing gas are regulated such that at least 85% of the H_2S component of the initial feed gas mixture is converted to S^0 and H_2O by the first and second stages together.

[0021] In certain embodiments, the process includes regulating the concentration of O_2 in the initial feed gas mixture, regulating the amount of O_2 provided in the second incremental amount of O_2 -containing gas, and regulating the amount of O_2 provided in the third incremental amount of O_2 -containing gas, such that at least 90% of the H_2S component of the initial feed gas mixture is converted to S^0 and H_2O by the first, second and third stages together. Preferably the product gas mixture contains less than 5% of the H_2S component of the initial feed gas stream as H_2S , at least 90% of the H_2S component of the initial feed gas stream as S^0 , and less than 10% of the H_2S component of the initial feed gas stream as SO_2 , by volume. By contrast, without staged oxygen the product gas mixture would typically contain up to 15% of the H_2S component of the initial feed gas stream as unreacted H_2S , 70-75% of the H_2S component of the initial feed gas stream as S^0 , and 8-12% of the H_2S component of the initial feed gas stream as SO_2 , by volume.

[0022] Certain embodiments of the process include maintaining a $\text{O}_2:\text{H}_2\text{S}$ molar ratio of less than 0.5 in the initial feed gas stream when contacting the initial catalyst portion. In certain preferred

embodiments the process also includes establishing a $O_2:H_2S$ molar ratio in the range of 0.30 to 0.43 at the beginning of each of the first, second and third stages.

[0023] In certain embodiments, the sulfur recovery process also includes passing the second or third stage product gas mixture into a cooling zone and cooling the gas mixture sufficiently to form liquid sulfur and a desulfurized effluent gas stream. Preferably the gas mixture is cooled to a temperature above the dewpoint of sulfur, to provide a partially cooled product stream, and then passing the partially cooled product stream into a sulfur condenser and further cooling the partially cooled product stream to the dewpoint temperature of gaseous elemental sulfur, or lower, but above the melting point of solid sulfur, such that the liquid phase of the sulfur product is favored. Liquid sulfur can be withdrawn from the sulfur condenser.

[0024] In certain embodiments, the sulfur recovery process includes maintaining the temperature of each catalyst portion above $300^{\circ}C$, preferably above $500^{\circ}C$ but less than $1,500^{\circ}C$. More preferably the catalyst temperature is maintained in the range of $700-1,300^{\circ}C$. In certain embodiments, the H_2S -containing gas stream is preheated before contacting the first catalyst portion. In certain embodiments, the H_2S feed gas stream is heated to about $200^{\circ}C$.

[0025] In certain embodiments, the process includes operating the process at a space velocity of at least about $20,000\ h^{-1}$. Some embodiments of the process comprise operating the reactor at superatmospheric pressure, and in some embodiments a catalyst contact time of no more than about 200 milliseconds is maintained.

[0026] In certain embodiments of the process the catalyst comprises Pt, Rh, Ru, Ir, Ni, Pd, Fe, Sn, Cr, Co, Re, Rb, V, Bi or Sb, or a combination of any of those metals, preferably Pt, Rh or a mixture thereof, more preferably a Pt-Rh alloy. The catalyst may also contain at least one alkaline element (*i.e.*, Mg, Ba or Ca) and/or one or more lanthanide element (*i.e.*, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb or Lu, or some combination of those elements), preferably Mg, Sm, Yb or Pr.

[0027] In some embodiments the catalyst employed in the sulfur recovery process comprises platinum and either magnesium oxide or samarium oxide. In some embodiments the catalyst comprises rhodium and samarium oxide. In some embodiments the catalyst comprises a refractory support chosen from the group consisting of one or more oxides of Al, Zr, Mg, Ce, Si, La, Sm and Yb. In certain embodiments the catalyst comprises a platinum-rhodium alloy deposited on a lanthanide oxide coated refractory support, preferably a samarium oxide coated refractory support, or comprises a platinum-rhodium alloy on an alkaline earth oxide coated refractory support, preferably an magnesium oxide coating. In still other embodiments, the catalyst comprises at least one carbided

metal such as a carbided platinum-rhodium alloy deposited on a magnesium oxide coated refractory support. The catalyst used in the process can have a gauze or monolith structure or can have a divided structure made up of a plurality of units. The units can comprise, for example, particles, granules, beads, pills, pellets, cylinders, trilobes, extrudates or spheres. In certain embodiments each particle or unit is less than 25 millimeters in its longest dimension, and in some embodiments less than 10 millimeters.

[0028] In accordance with another aspect of the present invention, a sulfur recovery system is provided that comprises a reactor having multiple reaction zones in serial flow arrangement. Each reaction zone comprises a catalyst having activity for catalyzing the partial oxidation of H_2S to elemental sulfur and water in the presence of O_2 , and each reaction zone has an inlet for introducing an O_2 -containing gas stream into the respective reaction zone. Preferably the reactor is capable of withstanding the highest temperature that the partial oxidation process may produce, *e.g.*, at least about $1,500^{\circ}C$. The system also includes a cooling zone comprising a sulfur condenser that has a liquid sulfur outlet and a desulfurized gas outlet. In certain embodiments the cooling zone comprises a plurality of thermally conductive tubes, and preferably includes at least one thermal insulator between the reaction zone and the thermally conductive tubes. In some embodiments the thermal insulators comprise ferrules that are made of a refractory material and which are attached to the thermally conductive tubes. In certain embodiments the cooling zone comprises a heat exchanger such as, for example, a boiler.

[0029] In certain embodiments the system also includes at least one tail gas treatment unit, and in some embodiments a heater is disposed between the desulfurized gas outlet and the tail gas treatment unit. These and other embodiments, features and advantages of the present invention will become apparent with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] For a more detailed description of the present invention, reference will now be made to the accompanying Figures, wherein:

[0031] **Fig. 1** is a schematic representation showing the components of a preferred embodiment of a sulfur recovery system according to the present invention.

[0032] **Fig. 2** is a schematic representation showing in cross-section a partial oxidation reactor adapted for three-stages of oxygen/air addition, in accordance with an embodiment of the present invention.

[0033] Fig. 3 is a graph showing the performance of a representative catalyst in an H₂S partial oxidation reaction operated over a range of air/H₂S ratios.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0034] High oxygen concentration in the O₂/H₂S reactant gas mixture that is fed to the catalytic partial oxidation reactor causes undesirable SO₂ formation. An SO₂ yield of 8-12% has been observed even under stoichiometric air/H₂S conditions of Reaction 5 (*i.e.*, 2.4). This indicates that a part of the H₂S feed is oxidized to SO₂ because of the oxygen rich atmosphere seen in the radiation shield (*e.g.*, alumina) and/or at the shield-catalyst interface. Only the remainder of the H₂S enters the catalyst bed. In other words, the air that is added at the front of the reactor is used up quickly and the oxidation to SO₂ occurs at the front of the catalyst bed. Thus, minimizing the SO₂ yield is less dependent on the flow rates employed, but is more dependent on the oxygen/H₂S ratio. A series of tests were performed to establish the feasibility of staging oxygen addition in the catalytic partial oxidation process in order to reduce or eliminate SO₂ formation. Those tests are described below in the Examples. In accordance with the results of those tests, a staged oxygen addition reactor configuration and process have been devised. Generally described, the process includes introducing a controlled amount of air with the H₂S feed to the front of the catalyst bed. The controlled amount is preferably just enough to minimize SO₂ production, *i.e.*, low air/H₂S ratio (about 1.4 – 2.0, preferably no more than about 2.4). Air is added in an incremental or staged manner along the catalyst bed so that the reaction is always O₂-limited, and thus selective for primarily S⁰ product. Preferably the air/H₂S ratio at each subsequent stage is also maintained at about 1.4 - 2.0. Staged oxygen addition to the H₂S catalytic partial oxidation process will increase net H₂S conversion and S⁰ yield, and will decrease SO₂ yield. Preferably selectivity for SO₂ is less than 10%, more preferably less than 5% and still more preferably less than 1%. The temperature at the front of the catalyst bed will also be lower when SO₂ is not being produced. Overall, the O₂ requirement for the process is also reduced.

[0035] A basic SPOC-IIITM sulfur recovery system 1, shown in Fig. 1, includes reactor 10 and cooling zone 110. Cooling zone 110 includes a heat exchanger 90 and a sulfur condenser 100. Depending on the purity of the H₂S stream, the particular contaminating gases included in the feedstock, and the purity requirements for the emerging gas stream, the system may also include a heater 120 and one or more tail gas clean up unit 130. The reactor is preferably similar to the short contact time (*i.e.*, 200 milliseconds or less)/fast quench (*i.e.*, less than one second) reactors that are

used for carrying out the catalytic partial oxidation of light hydrocarbons and the catalytic partial oxidation of hydrogen sulfide, as described in co-owned U.S. Patent No. 6,403,051. In the present case, the reactor is modified to provide for introduction of oxygen or an O₂-containing gas incrementally and at desired intervals along the catalyst bed.

[0036] Fig. 2 illustrates schematically an enlarged cross-sectional view of a staged oxygen addition reactor 10 of Fig. 1, together with a portion of cooling zone 110. Very generally described, the reactor is essentially a tube made of materials capable of withstanding the temperatures generated by the exothermic catalytic partial oxidation reaction (Reaction 5, above). Reactor 10 includes a feed gas inlet 20, a reaction zone 30, a reacted gas zone 80 and at least one product gas outlet 50. Reaction zone 30 preferably includes a thermal radiation shield or barrier 32 positioned immediately upstream of a catalyst 34 in a fixed-bed configuration. Radiation barrier 32 (also referred to as a thermal shield) is preferably a porous ceramic or refractory material that is suited to withstand the reactor operating temperatures and provide sufficient thermal insulation to the feed gas mixture to prevent gas phase reactions (pre-ignition) before reaching the catalyst 34 in zone 30. Suitable refractory barrier materials (e.g., alpha alumina) are well known in the art. A second barrier 36, which may be the same as barrier 32, is preferably positioned on the downstream side of catalyst 34 (catalyst floor) to retain the catalyst bed, as discussed in more detail below. In commercial scale operations the reactor is constructed of or lined with any suitable refractory material that is capable of withstanding the temperatures generated by the exothermic catalytic partial oxidation reaction. At intervals along the catalyst 34 are one or more O₂ inlets 22, 24. In a preferred configuration schematically shown in Fig. 2, oxygen is introduced in three stages through a first inlet 20 and supplementary inlets 22 and 24.

[0037] Downstream from reaction zone 30 is reacted gas zone 80 which includes at least one outlet 50 for the product gases from reaction zone 30. Barrier 36 is preferably capable of providing sufficient thermal insulation to the product gas mixture 38 leaving reaction zone 40 to permit the gases to begin cooling in reacted gas zone 80 as they move rapidly toward the reactor outlet 50. Catalyst 34 is positioned in reaction zone 30 in the flow path of the feed gas mixture introduced via inlet 20, and can have any suitable geometry. For example, it could be in the form of one or more layers of wire gauze, a monolith, or a bed of discrete or divided structures held between two porous refractory disks (radiation barriers 32,36). Suitable catalyst compositions are described in more detail below in the subsection entitled "H₂S Partial Oxidation Catalysts."

[0038] As shown in **Fig. 2**, reactor 10 includes an inlet 20 for the feed gas mixture containing H_2S and an initial increment of O_2 . The feed gases may be introduced as a mixture or fed separately and mixed upstream from the first reaction zone 30. A static mixer, such as a group of vanes projecting from the walls of a concentric perforated pipe, may be employed. At least one separate O_2 injection opening is positioned at (a) predetermined point(s) along the catalyst. In a preferred configuration, a pair of O_2 inlets 22 are positioned downstream from the top of the catalyst and another pair of O_2 inlets 24 are located downstream from inlets 22. It should be understood that the configuration of the reactor and the position of the feed injection openings could be configured in a variety of ways without affecting the principles or operation of the present system, as long as staged or incremental addition of oxygen to sequential portions of the catalyst is provided for.

[0039] Adjacent reactor outlet(s) 50 is a heat exchanger 90, which can be a waste heat or fire tube boiler, for cooling the second stage product gas mixture. Heat resistant ferrules 82 are embedded in refractory material 84 that lines at least the reaction zone and adjacent portions of reactor 10 that are exposed to high temperatures (e.g., $1,300^\circ\text{C}$ or more). Tube sheet 94 is a divider between the hot product gases and the boiling water where the second stage product gas mixture exits the reactor and enters heat exchanger 90, and contains a plurality of thermally conductive tubes 96 that extend from the process (reacted) gas outlet 50 of reactor 10 through heat exchanger 90. The tube sheet 94 and tubes 96 are preferably made of carbon steel. Since the carbon steel of the tubes and tube sheet cannot stand the high temperatures of the process gas, which can reach $1,300^\circ\text{C}$ or more, temperature protection for the metal is needed. Ferrules 82 connect to tubes 96 and, together with tube sheet 94, force the product gas mixture to exit the reactor by going through the inside of tubes 96, and heat exchanger 90 includes an outlet for steam. Water that is contained by the shell of the heat exchanger surrounds the outside of tubes 96. For most of tube sheet 94, including tubes 96, this protection is afforded by the boiling water. Preferably ferrules 82 are made of a refractory ceramic material and extend into tubes 96 as far as necessary to protect the metal tubing from exposure to excessively high temperatures.

[0040] Referring again to **Fig. 1**, following heat exchanger 90 is a sulfur condenser 100 for further cooling the process gas and providing for the removal of liquid sulfur product. In processes in which the cooled syngas mixture that emerges from condenser 100 still contains an undesirable amount of unreacted H_2S or other sulfur-containing gas, the assembly may further include a heater 120 and at least one tail gas cleanup unit 130. Tail gas cleanup unit 130 can include a hydrogenation stage followed by water removal, H_2S absorption, and recycle of the H_2S (Shell SCOT™ or Parsons BSR-

MDEA™, for example), or cleanup unit 130 may include an incinerator followed by SO₂ absorption (WELLMAN-LORD™, bisulfite salt or thiosulfate salt, for example), or liquid phase oxidation to sulfur by iron salts (LO-CAT™ or vanadium salts (STRETFORD™, for example), to meet regulatory emissions requirements.

Process for Recovering Sulfur from an H₂S-containing Stream

[0041] In an exemplary mode of operation the above-described apparatus is set up at a refinery to receive a waste gas stream that contains a level of H₂S that is too great to be safely released into the atmosphere. In operation, a reactant gas mixture containing H₂S and a less-than-stoichiometric amount, A, (where A = molar ratio O₂:H₂S) of O₂ enters reactor 10 at inlet 20, as shown in Fig. 2. The H₂S containing stream and the initial or first stage O₂-containing stream may be introduced together as a rapidly flowing reactant gas mixture or they may be fed separately into the reactor and mixed immediately upstream from reaction zone 30 in mixing zone 12. Molecular oxygen is provided in the form of air, pure oxygen, or an air/oxygen mix. If the H₂S-containing gas and the O₂-containing gas are introduced separately at the top of reaction zone 30, the feed injection openings can be configured in any of a number of different ways without affecting the principles or operation of the present system. A static mixer, such as a group of vanes projecting from the walls of a concentric perforated pipe, is one suitable option. The reactor may include a mixing zone 12 immediately upstream from barrier 32. Void spaces in the reactor are preferably avoided so as to minimize the occurrence of undesirable gas phase reactions between the feed gas components before entering reaction zone 30. The initial H₂S-containing stream may contain, for example, as little as 1% H₂S, or it could contain 3-25% H₂S as found in many natural gas formations, or it may even be an acid gas stream containing up to 100% H₂S (by volume). The minimum concentration H₂S in the H₂S-containing feed is that which will provide the minimum partial vapor pressure of gaseous elemental sulfur needed to condense sulfur liquid under the selected operating conditions of the process.

[0042] In order for sulfur vapor to condense from the vapor phase to the liquid phase, the sulfur in the vapor phase must be in equilibrium with sulfur in the liquid phase. According to Raoult's Law, this occurs where the mole fraction of the sulfur vapor times the total system pressure is equal to the vapor pressure of the sulfur liquid times its mole fraction or:

$$Y_S P_T = X_S P_S^{\text{sat}} \quad (6)$$

where Y_s = mole fraction of sulfur vapor, P_T = total pressure, X_s = mole fraction of sulfur vapor over the liquid phase, and P_s^{sat} = vapor pressure of pure liquid sulfur. A combination of low P_T of the system and the gas components of the present process make the gas phase behave nearly ideally, hence the use of the Raoult's law simplification.

[0043] Thus, at the conditions nominally expected in a process according to Equation 5, the left side of the Raoult equation is merely the partial pressure of the sulfur vapor. Sulfur is the only component of the mixture that would be expected to condense out of the mixture at the temperature of operation of a conventional sulfur condenser, about 260-375°F. Under those conditions, the mole fraction of sulfur in the liquid would be very close to 1. The right side of the equation is then the vapor pressure for sulfur vapor above a saturated sulfur liquid. Thus liquid sulfur could only be present when the partial pressure of sulfur in the vapor phase is equivalent to or greater than the vapor pressure of a saturated sulfur liquid. In accordance with standard published sulfur condensation curves, in a sulfur condenser operated at 260-375°F, and 1 atm pressure, the partial pressure of sulfur required in order to condense any sulfur liquid is between .001 and .01 atm or 0.001 - 0.01 mole fraction elemental sulfur vapor at 1 atm pressure.

[0044] Prior to contacting the first portion of the catalyst, the feed gas mixture is shielded by radiation barrier 32 from heat that is generated downstream in the process in first reaction zone 30. Preferably the temperature of the feed gas mixture is increased up to about 200°C to facilitate initiation of the reaction by preheating at least one of the feeds. In addition to manipulating the amount of available oxygen by incremental addition to the process, it is also preferable to keep the gases thoroughly mixed to avoid pockets of high O_2 concentration from occurring and to further deter complete oxidation of H_2S from taking place to form undesirable SO_2 . The contact time between the oxygen and H_2S is also preferably minimized to prevent having a stagnant explosive mixture form in the reactor. Minimum contact time between the O_2 and H_2S is facilitated by placing inert filler in any void spaces in the piping upstream of the reaction zone.

[0045] The molar ratio of air: H_2S is preferably at least 1.4 but not as much as 2.4 in the initial feed gas mixture (first catalytic stage). A preferred range is 1.4 – 2.0 air/ H_2S . In the case of a pure O_2 feed, the molar ratio of O_2 : H_2S in the initial feed gas mixture is at least 0.30 but not as much as 0.5. A preferred range is 0.3 – 0.43 O_2 / H_2S . The initial feed gas mixture contacts a first portion of the catalyst (adjacent shield 32) whereupon part of the H_2S content of the flowing stream of gases is converted to S_0 and H_2O , and the process gas stream then enters a second portion of the catalyst (second catalytic stage). An additional amount of molecular oxygen introduced through one or more

inlet 22 and mixed with the rapidly flowing process gas stream as it enters the second catalyst portion. This additional amount of oxygen, ($=B \times \text{H}_2\text{S flow}$, where "H₂S flow" is the flow rate of the H₂S at the front end of the catalyst bed and "B" is the molar ratio O₂:H₂S added to the second stage) is also a less than stoichiometric amount required to partially oxidize the unreacted H₂S carried over from the first stage. The second stage feed gas mixture comprises gaseous elemental sulfur, steam and unreacted H₂S from the first stage. Preferably the molar ratio of O₂:H₂S in this second stage feed gas mixture is also at least 0.30 but less than 0.5. As the second stage feed gas mixture flows past the second catalyst portion part of the remaining H₂S is converted to S₀ and H₂O.

[0046] The process gas mixture leaving the second catalytic stage comprises cumulative amounts of gaseous elemental sulfur and steam produced in the first and second catalytic stages and contains a reduced amount of unreacted H₂S compared to the reacted gas mixture leaving the first catalytic stage. Because the partial oxidation reactions in the first and second stages are carried out under relatively oxygen-starved conditions, little or no SO₂ is produced at the same time. As depicted in the preferred reactor configuration schematically illustrated in Fig. 2, a further incremental amount of molecular oxygen ($=C \times \text{H}_2\text{S flow}$, where "H₂S flow" is the flow rate of the H₂S at the front end of the catalyst bed and "C" is the molar ratio O₂:H₂S added to the third stage) is introduced through one or more inlet 24 that is aligned with a third portion of catalyst. The oxygen stream, supplying the desired incremental amount of O₂, is mixed with the rapidly flowing process gas stream as it enters the second catalyst portion. This additional amount of oxygen is preferably less than or equal to the stoichiometric amount required to partially oxidize the unreacted H₂S remaining from the second stage. Together the first, second and third incremental ratios of oxygen/H₂S supplied in the respective first, second and third catalytic stages preferably add up to 0.5 (*i.e.*, $(A + B + C)/\text{H}_2\text{S flow} \leq 0.5$), thus satisfying the total molar amount of oxygen in the 1:2 O₂/H₂S molar ratio required for the partial oxidation reaction (Equation 5), as set forth above.

[0047] In a simple process and reactor configuration the oxygen or air stream is split between the initial inlet and each subsequent inlet or stage so that an equal fraction of the total stoichiometric amount of O₂ required to convert the H₂S in the feed gas stream flows into each respective catalyst portion. For example, in a three-stage configuration, each stage may receive 1/3 of the total stoichiometric amount of oxygen required to satisfy the 0.5 molar ratio of the H₂S partial oxidation reaction ("SPOX" reaction). Alternatively, the incremental amount of air or oxygen available at a particular stage could be more or less than that which is provided to another portion of the catalyst, in order to manipulate the yield or selectivity of the process. Staged addition of oxygen to the flowing process gases while contacting sequential portions of catalyst will help reduce the occurrence of

unwanted side reactions that might otherwise rapidly occur during or after mixing of O_2 with the H_2S but prior to contacting the catalytic surfaces. For instance, in a three-stage process, the first stage may receive molecular oxygen in a molar ratio of 0.30 to 0.43 O_2/H_2S (or 1.4 to 2.0 air/ H_2S), with respect to the initial H_2S concentration. Each of stages two and three may be fed O_2 in molar ratios which together total 0.07 to 0.20 (with respect to the H_2S concentration in the initial feed), such that the total molar ratio of O_2 for the process is less than or equal to the desired stoichiometric 0.5 molar ratio O_2/H_2S . Preferably the partial oxidation reaction taking place in each stage is oxygen limited to minimize SO_2 formation.

[0048] The contact time of the feed gas stream with the catalyst is less than about 200 milliseconds, preferably less than 50 milliseconds, and still more preferably less than 20 milliseconds. A contact time of less than 10 milliseconds is highly preferred. When referring to a wire gauze catalyst, the contact time may be calculated as the wire diameter divided by the feed gas stream velocity at inlet conditions (*i.e.*, temperature and pressure at the inlet to the reactor). When employing a catalyst monolith or packed bed of divided catalyst, the surface area, depth of the catalyst bed, and gas flow rate (space velocity) are preferably managed to ensure the desired short contact time (*i.e.*, less than 200 milliseconds). It is well known that contact time is inversely proportional to the "space velocity," as that term is customarily used in chemical process descriptions, and is typically expressed as volumetric gas hourly space velocity in units of h^{-1} . Preferably the partial oxidation of H_2S in the first reaction zone is carried out at superatmospheric pressure (*i.e.*, greater than 1 atmosphere (100 kPa), more preferably >2 atmospheres (200 kPa)), and the gas hourly space velocity (GHSV) is at least $20,000 h^{-1}$, preferably at least $100,000 h^{-1}$.

[0049] After the rapidly moving feed gas mixture passes barrier 32 it flows past catalyst 34 in reaction zone 30 and where it becomes instantaneously heated sufficiently to initiate an oxidation reaction, the temperature quickly reaching the range of $700^{\circ}C$ - $1,500^{\circ}C$, preferably $850^{\circ}C$ - $1,300^{\circ}C$ as the partial oxidation reaction proceeds. The catalyst bed 34 is heated as a result of the exothermic chemical reaction occurring at its surface and maintains the stated partial oxidation reaction temperature range. It is best to avoid contacting the catalyst at a temperature at or below the dewpoint of sulfur. In some cases it may be helpful to heat catalyst 34 with external means at startup of the process, so as to initiate the exothermic oxidation reactions on the catalyst. This initial heating (*e.g.*, to about $300^{\circ}C$ - $500^{\circ}C$) can also be accomplished by briefly spiking the feed gas mixture with a readily oxidizable gas to heat up the catalyst sufficiently to initiate the H_2S partial oxidation reaction. Once the reactor is running, the partial oxidation reaction is preferably autothermal (*i.e.*,

the exothermic partial oxidation reaction supplies the heat needed to perpetuate the partial oxidation reaction). The rapid heating of the reactant gas mixture as a result of contact with the hot catalyst promotes fast reaction rates. Maintaining the preferred <200 millisecond range dwell time of the reactant gas mixture on the catalyst produces a favorable balance between temperature elevation due to the exothermic partial oxidation reaction and the convective removal of heat from the reaction zone 30 by the rapidly moving product gas stream. Thus, sufficient heat is generated to maintain the catalyst temperature in the range of 700°C - 1,500°C, more preferably in the range of about 850°C - 1,300°C.

[0050] The catalyzed reaction goes quickly by the direct oxidization of the H₂S to form sulfur and water according to Reaction 5. The most likely value for x in Reaction 5 at the preferred temperatures and pressures of the presently disclosed process is $x = 2$. Small amounts of light hydrocarbon, if present in the H₂S feed, will likely be partially oxidized at the same time to CO and H₂ under the H₂S catalytic partial oxidation reaction conditions, if the catalyst in reaction zone 30 possesses at least some activity for catalyzing the CPOX reaction. Preferably the totality of the H₂S catalytic partial oxidation reactions carried out in reaction zone 30 is optimized such that the conversion of the H₂S component to gaseous elemental sulfur is maintained at the maximum possible level (*i.e.*, the produced elemental sulfur is not lost through oxidation to SO₂.) Optimization of the reaction includes maintaining the O₂ concentration in each catalytic stage at a less-than-stoichiometric O₂/H₂S molar ratio (*i.e.*, less than 0.5). An oxygen-limited, multi-staged O₂ addition is preferred for achieving maximum total conversion of H₂S to elemental sulfur without allowing an excessive amount of SO₂ formation. By employing the second SPOX stage to partially oxidize the unreacted H₂S carried over from the first stage, the S⁰ yield is increased to at least 85%. Using the third SPOX stage to convert the small amount of H₂S remaining in the process gas stream, the S⁰ yield is further increased to at least 90%.

[0051] The rapidly flowing gases, containing primarily S⁰ and H₂O with minimal amounts of SO₂, H₂S and H₂ exit reaction zone 30 through barrier 36. Preferably the product gas mixture contains less than 5% of the incoming H₂S as H₂S, at least 90% of the incoming H₂S as S⁰ and less than 5% of the incoming H₂S as SO₂ by volume. The H₂S catalytic partial oxidation reaction is exothermic, and the reactor is preferably operated adiabatically (*i.e.*, without the loss of heat aside from convective losses in the exiting gas). From reaction zone 30, the reacted gases enter cooling zone 110 (as shown in Fig. 1) which includes the product gas zone 80 followed by a heat exchanger 90 and then a sulfur condenser 100. The barrier 36 shields the reacted gases from the hot catalyst and the temperature of

the reacted gases starts to decline in product gas zone 80. In heat exchanger 90 the product gases are cooled in thermally conductive tubes 96 to below 425°C, preferably below about 340°C, but not below the dew point of sulfur. The water surrounding tubes 96 is raised to its boiling point by heat conducted away from the hot gas through tubes 96. It is preferable to capture the evolved steam for secondary use. Since the boiling water remains at a constant temperature, and since the metal conducts heat so readily, tubes 96 and most of tube sheet 94 attain temperatures only slightly above the temperature of boiling water. This is not the case for the portions of tube sheet 94 where tubes 96 connect at joints 92. Without thermal protection, these joints and the first part of the tube would see temperatures far exceeding the safe operating limits for the metal. The refractory covering 84 and heat resistant ferrules 82 provide insulation for these relatively unprotected areas of metal. Thus, only metal surfaces that are adequately exposed to the circulating water will encounter the hot gases. The rapid cooling that occurs in the boiler drops the temperature of the reacted gases to below about 425°C and thus ceases the chemical reactions. Alternatively, another suitable cooling technique could be employed instead of a boiler. The water vapor, gaseous elemental sulfur, and CO₂, plus any incidental gases or combustion products, flow from heat exchanger 90 into sulfur condenser 100, where they are cooled further until the dew point of elemental sulfur is reached.

[0052] High levels of conversion and the lack of SO₂ in the product stream will usually make it unnecessary to proceed to tail gas treatments in order to achieve an acceptable level of desulfurization in the resulting gas stream. The liquid sulfur that forms in sulfur condenser 90 may be removed from the condenser by way of outlet 102. Under the preferred optimal operating conditions, and when only a minor amount of other gases are present in the H₂S rich gas feed, the desulfurized gas emerging from the condenser may be safely vented into the atmosphere without constituting an environmental burden. In some situations, however, such as where the H₂S-containing feedstock contains an appreciable amount of contaminating gases, it may be desirable to remove even very low levels of sulfurous or other components before the residual gases are vented into the atmosphere. In such case, the gas leaving sulfur condenser 90 may be reheated by heater 120 and sent to tail gas treatment unit 130, as shown in Fig. 1, or a series of tail gas treatment units, if necessary for a particular application.

[0053] In tail gas unit 130, residual sulfur-containing components are preferably converted to H₂S, sulfur or SO₂. H₂S from outlet 132 can be recycled to the present process. Sulfur from a tailgas cleanup unit 130 may be recovered from outlet 134 as a solid or liquid and sold as valuable elemental sulfur. SO₂ may be absorbed into bisulfite or thiosulfite salt solutions that may be sold. The effluent

gas, meeting environmental emissions regulations, may then be discharged at outlet 136 to the atmosphere.

[0054] Ensuring H₂S catalytic partial oxidation reaction promoting conditions in the first reaction zone may include adjusting the relative amounts of H₂S, O₂ and other oxidizable components (*e.g.*, hydrocarbon) in the feed gas mixture. For example, an amount of O₂ in excess of the preferred minimum molar ratio of O₂/H₂S stated above is preferably provided if the H₂S-containing feed also contains a light hydrocarbon or another oxidizable compound that consumes oxygen under the same process conditions. Reaction promoting conditions may also include adjusting the amount of preheating of the reactant gas mixture and/or the catalyst, adjusting the operating pressure of the reactor, which is preferably maintained above atmospheric pressure, more preferably in excess of two atmospheres pressure. Increasing or decreasing the space velocity of the feed gas mixture, which is influenced not only by pressure but also by the configuration of the catalyst bed, its porosity and the associated pressure drop, also can be used to favor the H₂S partial oxidation reaction.

[0055] Although the exemplary process set forth above, and the reactor configuration schematically illustrated in Fig. 2, describe the use of two or three H₂S catalytic partial oxidation stages, it can be readily appreciated that more than three sequential stages could also be used in instances where it is desirable to remove even very small residual amounts of H₂S from the final gas stream. For each added stage one or more oxygen inlet like inlets 22,24 is added at a desired point along the catalyst bed of the reactor for introducing another incremental (less than stoichiometric) amount of oxygen to a further portion of the catalyst. In that case, it may be desirable to reposition the stages closer together along the catalyst bed. While it is preferred to keep the number of air addition stages to less than four, depending on the desired overall S yield, additional air addition stages can be included by choosing suitable catalyst bed length and gas flowrates to avoid excessive pressure drop and capital cost.

[0056] By reducing the amount of equipment necessary to obtain a high level of sulfur recovery from an H₂S containing feed gas, the total pressure drop through the sulfur plant can be greatly reduced. Standard air demand analyzers that operate based on measured H₂S/SO₂ ratio at the exit of each catalyst stage can be used. As the H₂S/SO₂ ratio decreases, O₂ addition can be decreased to minimize SO₂ formation. Such control can be fed back to the feed flow controllers to achieve high S selectivity and low SO₂ selectivity. Since Claus plants are normally limited by the amount of pressure drop due to the low pressure operation, the present system advantageously allows for capacity expansion by the user. The new short contact time sulfur recovery processes and the simplified sulfur process plants described herein are suitable for use in most refinery or gas plant

applications such as hydrotreaters, cokers and fluid catalytic crackers where H_2S -containing waste gases are typically produced and desulfurization is needed before the waste gas can be safely vented into the atmosphere. As a result of using the present system, there is minimal direct stack emission from the sulfur recovery unit into the air surrounding the plant. Another suitable use for the disclosed apparatus and process is for cleaning up natural gas well effluents at the well site. Such emissions typically contain about 1 - 5% H_2S by volume and can contain even as much as 25%.

H_2S Partial Oxidation Catalysts

[0057] Referring again to Fig. 2, for simplicity the catalyst 34 of first reaction zone 30 is depicted as a particle bed. It could also be one or more wire mesh or gauze layer, a monolith or a divided bed containing any of a variety of geometries. The catalyst is preferably configured so that only a first fraction of the feed gas mixture contacts the catalytically active surfaces while the balance of the reactant gas mixture serves to quickly cool the first fraction and prevent the oxidation reaction from proceeding too far in the first reaction zone. The catalyst may be formed entirely of catalytic material, or it may comprise one or more catalytic components supported on a non-catalytic refractory support. When the catalyst is in the form of a gauze, it is preferably one or more layers of a substantially planar, flexible woven metal-containing or metal-coated screen or gauze having about 20-120 mesh. More preferably, it is a single gauze of metal wires, or a short stack of gauzes, of diameter compatible with the diameter of the reactor. In a laboratory scale reactor about 25 cm in length, the catalysts are preferably about 25 micrometers (μm) to about 2.5 millimeters (mm) in diameter.

[0058] **Metal Gauzes.** One type of catalyst is in the form of one or more layers of substantially planar, flexible woven metal-containing or metal-coated screen or gauze having about 20-120 mesh and diameter compatible with the inner diameter of the reactor. Suitable metals that may be formed into a gauze or deposited onto a non-catalytic gauze support include platinum, rhodium, ruthenium, iridium, nickel, palladium, iron, cobalt, rhenium and rubidium, or a mixture of any of those metals. Some of the more preferred gauze-type catalysts are made of about 87-93% by weight (wt%) Pt and about 7-13 wt% Rh (wt% based on total weight of the catalyst device). Alternative catalyst structures or devices may be in the form of one or more perforated disks, honeycomb-like structures, etched foils or any other suitably active structure that provides the desired gas flow rate to effect the desired partial oxidation.

[0059] **Rh on an Alkaline Earth or Lanthanide-modified Refractory Support.** Another type of catalyst that is active for catalyzing the direct partial oxidation of H_2S to elemental sulfur comprises

about 0.005 to 25 wt% Rh, preferably 0.05 to 25 wt% Rh, and about 0.005 to 25 wt% of a lanthanide element (i.e., La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu), preferably samarium, ytterbium or praseodymium or an alkaline element (i.e., Mg, Ca or Ba) preferably magnesium, in the form of the metal and/or metal oxide coating a refractory monolith or a plurality of distinct or discrete structures or particulates. An especially preferred Rh-Ln catalyst contains about 0.5-10 wt% Rh and about 0.5-10 wt% Sm on a refractory support, especially where the ratio of rhodium to Sm is in the range of about 0.5 - 2. For example, one active H₂S partial oxidation catalyst is prepared by depositing 2-6 wt% Rh onto a layer of 2-5 wt% Sm which coats a partially stabilized (MgO) zirconia ("PSZ") monolith having about 45-80 pores per linear inch. Weight percents (wt%) refer to the amount of metal component relative to the total weight of the catalyst, including the support, if any. Suitable PSZ monoliths are commercially available from Vesuvius Hi-Tech Ceramics Inc., Alfred Station, New York. Other monolith support structures or catalyst configurations include a disk with multiple perforations formed therethrough, a honeycomb-like structure, an etched foil and any other structure that provides the desired amount of transparency to permit the 200 millisecond or less contact time to effect the desired H₂S partial oxidation reaction.

[0060] Pt-Rh Alloy. While many of the above-described catalyst compositions have demonstrated good activity for catalyzing the partial oxidation of H₂S, and are satisfactory for a number of SPOC™ applications, some metals, such as Rh, suffer from deactivation with extended on stream use due to the formation of sulfur deposits and/or metal sulfide formation that removes the active catalytic form. The surprising discovery was made that this problem is greatly improved or solved completely by combining platinum with rhodium in the catalyst.

[0061] Pt-Rh Alloy on an Alkaline Earth or Lanthanide-modified Refractory Support. An especially good catalyst that is highly stable and active for catalyzing the direct partial oxidation of high concentrations of H₂S in a gas stream to elemental sulfur and water contains both platinum and rhodium supported on a samarium-modified refractory support such as the above-described supports and materials. A highly preferred catalyst is prepared by depositing about 0.1%-6 wt% Pt onto about 1-6 wt% Rh, which was previously deposited onto a refractory support that has been coated with about 2-5 wt% lanthanide oxide (preferably samarium oxide) or alkaline earth oxide (preferably magnesium oxide). Weight percent (wt%) is based on total weight of the supported catalyst. A preferred support is alumina granules, more preferably alpha-alumina. In the present investigations, the surprising synergy of the Pt and Rh components enhanced catalyst stability under H₂S catalytic partial oxidation reaction conditions, and when further combined with a lanthanide or alkaline earth oxide modifier provides an even better catalyst for syngas production. Catalyst stability refers to

resistant to (a) deactivation due to carbon or sulfur deposition, (b) chemical reaction between sulfur and the catalytic components and (c) volatilization of precious metal at reaction conditions. The stability is typically shown by a consistent and reproducible catalytic performance (*e.g.*, S yield with H₂S feed or syngas yield with light hydrocarbon feed).

[0062] The above-described Pt-Rh based catalysts are preferably in the form of either a wire gauze, a foam monolith, or in the form of a catalytically active material dispersed or deposited on a refractory support containing zirconia, alumina, titania, mullite, zirconia-stabilized alumina, MgO stabilized zirconia, MgO stabilized alumina, niobia or a mixture of any of those materials, or another suitable refractory material. For example, the catalyst can be structured as, or supported on, a refractory oxide "honeycomb" straight channel extrudate or monolith, made of cordierite or mullite, or other configuration having longitudinal channels or passageways permitting high space velocities with a minimal pressure drop. Such configurations are known in the art and described, for example, in *Structured Catalysts and Reactors*, A. Cybulski and J.A. Moulijn (Eds.), Marcel Dekker, Inc., 1998, p. 599-615 (Ch. 21, X. Xu and J.A. Moulijn, "Transformation of a Structured Carrier into Structured Catalyst"), which is hereby incorporated herein by reference.

[0063] A more preferred catalyst geometry comprises granules prepared by impregnating or washcoating the catalytic components, or their precursors, onto lanthanide or alkaline oxide coated refractory granules, calcining and reducing the catalyst, using techniques that are well known in the art. A catalyst bed for a the H₂S catalytic partial oxidation process may comprise a quantity of such impregnated or coated granules, or other forms of support such as beads, pills, pellets, cylinders, trilobes, extrudates, spheres, other rounded shapes or other manufactured configurations, or irregularly shaped particles. The supports preferably comprise a refractory material such as zirconia, alumina, cordierite, titania, mullite, zirconia-stabilized alumina, MgO stabilized zirconia, MgO stabilized alumina, niobia or a mixture of any of those materials, or another suitable refractory material. Alumina is preferably in the form of alpha-alumina, however the other forms of alumina have also demonstrated satisfactory performance.

[0064] The Pt-Rh/Mg and Pt-Rh/Ln catalysts also have superior activity for converting an H₂S stream containing a light hydrocarbon, such as methane, to elemental sulfur and synthesis gas, by way of concurrent CPOX and SPOC™ reactions carried out over the same catalyst in a single reaction zone, operating the reactor at hydrocarbon, H₂S and O₂ concentrations and process conditions that favor the formation of both sulfur, CO and H₂, as described in co-owned U.S. Patent No. 6,579,510 and U.S. Patent Application No. 09/625,710 filed July 25, 2000, each of which is hereby incorporated herein by reference.

[0065] Carbided Pt/Rh on a Refractory Support. Another unexpected discovery was that the gradual deactivation of rhodium, and others among the above-named SPOC™ catalysts, was also improved by carbiding the catalyst under gaseous hydrocarbon flow before, after or during the H₂S flow, under CPOX-promoting reaction conditions. An especially active catalyst that provides improved performance for converting H₂S to sulfur by direct partial oxidation (the H₂S partial oxidation process) is prepared by carbiding a Pt-Rh catalyst before exposing the catalyst to H₂S.

[0066] The carbiding process includes exposing the catalyst, in any of the forms described above, to light hydrocarbon (a C₁-C₅ hydrocarbon, preferably methane, ethane, propane or butane) under CPOX reaction conditions as described in co-owned U.S. Patent Application No. 09/625,710 filed July 25, 2000 or U.S. Patent Application No. 10/317,936 filed December 12, 2002. Preferably this hydrocarbon pre-treatment procedure (referred to herein as "carbiding") is carried out with the catalyst in place in the short contact time reactor. The carbiding treatment includes heating the catalyst to at least 700°C or up to about 1,500°C, preferably in the range of 850°C - 1,300°C, in the presence of the light hydrocarbon. Upon getting the catalyst up to CPOX operating temperature, the flow of hydrocarbon is stopped and the flow of H₂S containing gas is begun for sulfur removal and recovery under SPOC-III™ operating conditions. It is preferable to perform the carbiding treatment before exposing the catalyst to H₂S or other sulfur compound while the catalyst is at a temperature at which it can chemically react with sulfur or at which sulfur can condense on its active sites. In the carbiding treatment, it is preferable to mix the hydrocarbon with a small amount of oxygen or O₂-containing gas to deter or minimize coking of the catalyst during treatment. The amount of oxygen preferably does not exceed the stoichiometric amount necessary to support catalytic partial oxidation of the hydrocarbon (CPOX reaction), *i.e.*, a carbon:oxygen molar ratio of 2:1. If the catalytic components are also active for catalyzing the CPOX reaction, production of synthesis gas (CO and H₂) may commence during the pre-treatment step upon reaching a temperature sufficient to initiate the reaction. Without wishing to be bound by any particular theory, it is believed that, in the case of a Pt-Rh alloy catalyst, the formation of Rh and/or Pt carbide in which at least a substantial portion of the catalytic metal component exists in the same phase with carbon (e.g., RhC_x or PtC_x), which resists the formation of metal sulfide(s) that can deactivate the catalyst by covering the active centers. Thus, the stability and life of the catalyst on H₂S stream is increased or enhanced by the carbiding treatment.

[0067] The exemplary process described above and schematically depicted in **Fig. 2** use for simplicity the same catalyst composition in each of two or three catalytic stages. It is also

contemplated that the catalyst composition or the structural characteristics of the catalyst could be different from one stage to another, if desired. For example, to optimize selectivity the second or subsequent stage catalyst could be varied by lowering the Pt wt%. The flow rate could be optimized by making the second or subsequent stage catalysts more porous than the first stage and/or by modifying the size or shape of the catalyst supports.

Test Procedure for Estimating the Effect of Staged O₂ Addition

[0068] The effect of air/H₂S ratio at constant flow rate on the catalytic partial oxidation of H₂S was determined in a modified conventional flow apparatus using a quartz reactor with a length of 12 inches, an outside diameter of 19 mm and an inside diameter of 13 mm. Ceramic foam pieces of 99% Al₂O₃ (12 mm outside diameter x 5 mm thick, with 80 pores per linear inch) were placed before and after the catalyst as radiation shields. The catalyst bed including the radiation shields was approximately 12 mm in diameter x 8 cm in height. The inlet radiation shield also aided in uniform distribution of the feed gases. An Inconel-sheathed, single point K-type (Chromel/Alumel) thermocouple was placed axially inside the reactor, touching the top (inlet) face of the radiation shield. A high temperature S-Type (Pt/Pt 10% Rh) bare-wire thermocouple was positioned axially touching the bottom face of the catalyst, and was used to indicate the reaction temperature. The catalyst and the two radiation shields were tightly sealed against the inside walls of the quartz reactor by wrapping the shields radially with a high purity (99.5%) alumina paper. A 600-watt band heater set at 90% electrical output was placed around the quartz tube, providing heat to light off the reaction and preheat the feed gases. The bottom of the band heater corresponded to the top of the upper radiation shield.

[0069] In addition to the thermocouples placed above and below the catalyst, the reactor also contained two axially positioned, triple-point thermocouples, one before and another after the catalyst. These triple-point thermocouples were used to determine the temperature profiles of the reactants and products that were subjected to preheating and quenching, respectively.

[0070] The runs were conducted at a volumetric oxygen to methane ratio of 0.3-0.5, a preheat temperature of 200-250°C, and a combined flow rate of 2,500 – 7,000 cc/min (2.5 - 7 standard liters per minute (SLPM)), corresponding to a gas hourly space velocity (GHSV) of about 100,000 – 3,000,000 hr⁻¹, and at a pressure of 5 psig (136 kPa), except where specific process conditions are stated in the results that are given below. The reactor effluent was analyzed using a gas chromatograph equipped with a thermal conductivity detector.

[0071] The catalyst compositions employed in these tests are set out in the Examples which follow. The catalytic activity of representative catalyst compositions described above has been previously established using a similar test procedure, as disclosed in a related U.S. Patent Application No. 10/024167 which is hereby incorporated herein by reference.

[0072] The data reported in Table 1 were obtained after approximately 1 hour on stream at the specified conditions. The catalyst was stable under very high GHSV and varying H₂S/oxygen ratios. When the various Pt-Sm/Al₂O₃, Rh-Sm/Al₂O₃, and Pt-Rh-Sm/Al₂O₃ compositions described above were tested for their ability to catalyze the direct oxidation of H₂S to S⁰, the Pt-Rh-Sm combination demonstrated longer catalyst life compared to the samples containing only Pt-Sm or Rh-Sm. Catalyst life was primarily determined by the catalyst's resistance to deactivation due to coking or plugging by sulfide formation. These tests also showed a loss of catalyst performance when Sm was absent from the catalyst composition. Without wishing to be limited to a particular theory, it is believed that Sm deters solid reaction of the catalytic metals and the support material. For example, it is thought that Sm deters formation of metal aluminate compounds from the solid reaction of the Pt and/or Rh with the alumina support at SPOC™ reaction temperatures. The presence of Sm as the support modifier also improves the surface area (*i.e.*, dispersion) of the Pt and/or Rh. The latter property is believed to cause the improved S⁰ yield during the SPOC™ process. It was also observed that the addition of Sm to the support prior to application of the active metals lowered the reaction initiation (*i.e.*, light off) temperature. Using magnesium in place of samarium provided the same advantages described above, and also offers the advantage of lower cost. In a series of tests of the Pt-Rh/Mg and Pt-Rh/Sm catalysts, contact times of 9 milliseconds and less were obtained, and even a 2 millisecond contact time was obtained under the stated reaction conditions, providing excellent results in each case.

Table 1
Catalyst Performance for H₂S Catalytic Partial Oxidation

	Catalyst composition	H ₂ S flow (ml/min)	Air flow (ml/min)	N ₂ flow (ml/min)	H ₂ S conversion (%)	S yield (%)	SO ₂ yield (%)	Cause of deactivation
Without carbiding	3.9% Rh, 5.1% Sm on 80-ppi alpha-alumina foam (1 gram total weight)	633	1519	900	75.7	63.9	11.8	Sulfur formation on the catalyst (shown by SEM analysis)
		892	2141	900	78.4	65.8	12.7	
		1140	2736	900	79.7	65.9	13.8	
		1640	3936	1000	79.0	62.6	16.4	
With carbiding (Propane)	4.2% Rh, 5.2% Sm on 80-ppi alpha-alumina foam (1 gram total weight)	1195	4768	0	82.2	69.4	12.9	No deactivation for the run duration (6 hours)
		2195	5265	0	82.7	69.7	13.0	
With carbiding (Methane)	0.5% Pt, 5% Rh, 5% Sm on 1/16" α/γ -alumina extrudates (2 grams total weight)	761	1755	0	82.4	72.4	10.0	No deactivation for the run duration (10 hours)
		1520	3498	0	82.6	71.3	11.3	

Note: S and SO₂ yields are calculated as the product of H₂S conversion and S or SO₂ selectivity respectively. Nitrogen addition for the non-carbided catalyst was needed to lower the catalyst temperature.

[0073] Comparing the performance of the catalysts shown in Table 1, it can be seen that after carbiding a representative monolith supported Rh/Sm catalyst, superior S yield and catalyst stability was obtained despite increasing the flow rates by 100-200%. Without wishing to be bound by any particular theory, it is believed that the formation of metal carbide prevented the formation of sulfur or sulfide species on the catalyst. This, in turn, kept the active components from becoming deactivated and improved the partial oxidation of H₂S to elemental S. Combining Pt with Rh on Sm coated extrudates provided comparable conversion and selectivity and provided even longer life on stream without sulfur deactivation or coking (when light hydrocarbons are also present in the feed).

[0074] As mentioned above, a series of tests were performed to establish the feasibility of staging oxygen addition to the catalyst and process gas. In these studies, the effect of the air/H₂S ratio at constant flow rate on the activity and selectivity of the catalytic partial oxidation process over the indicated catalysts was determined. All catalysts were packed using 3/16" thick 80-ppi alpha-alumina foam as the radiation shield, and 5/8" thick 40-ppi alpha-alumina foam as the catalyst floor.

Example 1.

[0075] A catalyst having the composition 1% Rh, 4% Pt, 3% Mg on fused alpha-alumina pills, 4 grams was prepared and tested as described above. The H₂S flow rate was 850 ml/min, or 0.85 SLPM, and the reactant gas preheat temperature was 450°F (232°C). The results of those tests are shown in Table 3.

Table 3

Effect of Air/H₂S Ratio on H₂S Conversion and Product Selectivity

Air/H₂S Ratio	% H₂S Conversion	% Sulfur Yield	% SO₂ Yield	% H₂ Yield	% S⁰ Selectivity	% SO₂ Selectivity
2.37	84.48	72.79	11.66	6.65	86.16	13.80
2.26	83.76	73.17	10.55	6.40	87.36	12.60
2.16	82.77	73.65	9.09	6.46	88.98	10.98
2.07	81.64	73.75	7.86	6.56	90.33	9.63
1.97	79.97	73.20	6.74	6.66	91.53	8.42
1.87	85.61	82.09	3.50	4.29	95.89	4.09
1.77	76.25	71.61	4.60	6.78	93.92	6.04
1.67	74.45	70.71	3.71	6.95	94.98	4.98
1.57	72.11	69.08	3.01	6.95	95.79	4.17

Catalyst: 1% Rh, 4% Pt, 3% Mg on fused alpha-alumina pills

Example 2.

[0076] A catalyst having the composition 1% Rh, 4% Pt, 3% Mg on fused alpha-alumina pills, 4 grams was prepared and tested as described above. The H₂S flow rate was 950 ml/min, or 0.95 SLPM, and the reactant gas preheat temperature was 450°F (232°C). The results of those tests are shown in Table 4.

Table 4**Effect of Air/H₂S Ratio on H₂S Conversion and Product Selectivity**

Air/H₂S Ratio	% H₂S Conversion	% Sulfur Yield	% SO₂ Yield	% H₂ Yield	% S⁰ Selectivity	% SO₂ Selectivity
2.76	85.75	66.31	19.41	7.80	77.33	22.64
2.66	85.11	67.17	17.91	7.97	78.93	21.04
2.55	84.39	68.05	16.31	8.15	80.64	19.33
2.46	83.51	68.64	14.87	8.39	82.19	17.81
2.36	81.59	67.50	14.08	9.00	82.74	17.26
2.25	81.30	69.18	12.10	8.89	85.09	14.88
2.17	80.10	69.31	10.77	9.00	86.52	13.45
2.06	78.87	69.45	9.40	8.91	88.05	11.92
1.97	77.09	68.86	8.21	8.71	89.32	10.65
1.87	74.83	67.99	6.82	8.17	90.86	9.11
1.77	72.22	66.39	5.81	7.41	91.92	8.05
1.67	69.02	63.99	5.01	6.46	92.71	7.26
1.57	65.28	60.91	4.35	5.37	93.30	6.66
1.47	61.24	57.38	3.84	4.22	93.70	6.26
1.37	57.79	54.30	3.47	3.11	93.96	6.00
1.27	54.42	50.96	3.45	2.21	93.63	6.33

Catalyst: 1% Rh, 4% Pt, 3% Mg on fused alpha-alumina pills

Example 3.

[0077] A catalyst having the composition 4% Pt, 1% Rh, 3% Mg on MgO granules, 4 grams, was prepared and tested as described above. The H₂S flow rate was 1,050 ml/min, or 1.05 SLPM, and the reactant gas preheat temperature was 450°F (232°C). The results of those tests are shown in Table 5.

Table 5**Effect of Air/H₂S Ratio on H₂S Conversion and Product Selectivity**

Air/H₂S Ratio	% H₂S Conversion	% Sulfur Yield	% SO₂ Yield	% H₂ Yield	% S⁰ Selectivity	% SO₂ Selectivity
2.37	84.61	73.80	10.81	4.81	87.22	12.78
2.27	83.98	73.77	10.18	6.30	87.85	12.12
2.17	82.41	73.26	9.13	6.58	88.89	11.08
2.07	80.94	72.93	7.99	6.61	90.11	9.87
1.97	79.16	72.37	6.76	6.61	91.43	8.54
1.77	75.74	70.72	5.01	6.34	93.36	6.61
1.57	71.59	68.28	3.29	6.15	95.37	4.60
1.48	68.35	65.79	2.53	6.23	96.26	3.70
1.38	65.67	63.64	2.00	6.16	96.91	3.05

Catalyst: 4% Pt, 1% Rh, 3% Mg on MgO granules

Example 4.

[0078] A catalyst having the composition 2% Pt, 1% Rh, 2% Mg on MgO granules, 20-30 mesh, 3 grams was prepared and tested using the same laboratory scale reactor set-up as in the preceding examples and H₂S flow rate of 1.75 SLPM. The results of the test are presented in Fig. 3, showing the effect of Air/H₂S ratio on the SPOC™ variables H₂S conversion, sulfur yield and SO₂ yield over the range of air/H₂S ratios of 1.4 to 3.0.

Example 5.

[0079] A catalyst having the composition 1% Pt, 4% Rh, 1% Pt, 5% Sm on fused alpha-alumina pills, 4 grams, was prepared and tested as described above. The H₂S flow rate was 950 ml/min, or .95 SLPM, and the reactant gas preheat temperature was 450°F (232°C). The results of those tests are shown in Table 6.

Table 6**Effect of Air/H₂S Ratio on H₂S Conversion and Product Selectivity**

Air/H₂S Ratio	% H₂S Conversion	% Sulfur Yield	% SO₂ Yield	% H₂ Yield	% S⁰ Selectivity	% SO₂ Selectivity
2.36	86.24	73.40	12.81	6.70	85.11	14.85
2.26	84.44	73.56	10.85	7.21	87.11	12.85
2.16	83.67	74.16	9.48	7.35	88.63	11.33
2.06	82.54	74.23	8.28	7.55	89.93	10.03
1.97	81.62	74.55	7.04	7.78	91.34	8.63
1.87	80.40	74.44	5.93	8.04	92.58	7.38
1.77	78.62	73.53	5.05	8.31	93.53	6.43
1.67	77.14	73.27	3.84	8.31	94.99	4.98
1.57	74.48	71.15	3.30	8.25	95.53	4.43
1.47	71.46	68.66	2.77	7.70	96.09	3.87

Catalyst: 1% Pt, 4% Rh, 1% Pt, 5% Sm on fused alpha-alumina pills

[0080] In all of the foregoing examples, it can be seen that as the air/H₂S ratio is decreased, SO₂ yield and selectivity decrease with an increase in S⁰ selectivity. S⁰ yield, which is a product of H₂S conversion and S⁰ selectivity remains steady until the air/H₂S ratio is too low. This indicates that using any of these catalysts, a staged air configuration can be devised whereby the SO₂ yield is kept to a minimum and S⁰ yield can be increased to more than 85% in two stages and to more than 90% in three stages. For instance, using the H₂S conversion, S yield and SO₂ yield from Table 6 at 1.47 Air/H₂S ratio, the basis shown in **Table 7** was developed, assuming that the second and third catalyst stages will have the same performance (*i.e.*, % H₂S conversion, S yield, SO₂ yield), as the first stage at a given Air/H₂S ratio.

Table 7
THREE-STAGE AIR CONFIGURATION

	After 1 st Stage (actual)	After 2 nd stage (calculated)	After 3 rd stage (calculated)
	1 st stage Air/H ₂ S ratio = 1.47	2 nd stage Air/H ₂ S ratio = 1.47	3 rd stage Air/H ₂ S ratio = 1.47
Initial H ₂ S flowrate (SLPM) = 0.95 Corresponding air flow rate to the 1 st stage = 0.95 x 1.47 = 1.40 SLPM		At 1.47 Air/H ₂ S ratio and 0.27 SLPM H ₂ S to the 2 nd stage, corresponding air flowrate to the 2 nd stage = 0.27 x 1.47 = 0.40 SLPM	At 1.47 Air/H ₂ S ratio and 0.08 SLPM H ₂ S to the 3 rd stage, corresponding air flowrate to the 3 rd stage = 0.08 x 1.47 = 0.12 SLPM
	S = 68.7 % SO ₂ = 2.8 % H ₂ S = 28.5 % (This corresponds to 0.285 x 0.95 = 0.27 SLPM H ₂ S exiting 1 st stage and going to the 2 nd stage)	S = 68.7 + (28.5 x 0.687) = 88.3 % SO ₂ = 2.8 + (28.5 x 0.028) = 3.6% H ₂ S = 8.1 % (This corresponds to 0.081 x 0.95 = 0.08 SLPM H ₂ S exiting 1 st stage and going to the 2 nd stage)	S = 88.3 + (8.1 x 0.687) = 93.9 % SO ₂ = 3.6 + (8.1 x 0.028) = 3.6 % H ₂ S = 2.3 % (This will be the exit composition after three SPOC™ staged air stages. This calculation can be extended for four stages if needed.

[0081] After 2 stages, (Total Air/H₂S) ratio = (1.40+0.40)/0.95 = 1.89 and the S and SO₂ yields are 88.3% and 3.6% respectively. This compares with 74.4% and 5.9% yields at the same Air/H₂S ratio in a single stage as shown in **Table 6**.

[0082] After 3 stages, (Total Air/H₂S) ratio = (1.40+0.40+0.12)/0.95 = 2.02 and the S and SO₂ yields are 93.9% and 3.6% respectively. This compares with 74.2% and 8.3% yields at the same Air/H₂S ratio in a single stage as shown in **Table 6**. These comparisons show that addition of air in stages to the same catalyst bed has the advantage of making the S yields higher and SO₂ yields lower, while keeping the total oxygen requirement less than the stoichiometric amount.

[0083] In addition to the advantages of reduced SO₂ production and increased S⁰ yield, another advantage is that less air will be required, which in turn allows each stage to be much smaller in size because of the smaller gas volumes flowing, compared to a process and apparatus in which oxygen or air is introduced only in combination with the initial H₂S feed.

[0084] Definitions. As used herein, the term "about" or "approximately," when preceding a numerical value, has its usual meaning and also includes the range of normal measurement variations that is customary with laboratory instruments that are commonly used in this field of endeavor (*e.g.*, weight, temperature or pressure measuring devices), preferably within $\pm 10\%$ of the stated numerical value.

[0085] The terms "discrete" or "divided" structures or units refer to catalyst devices or supports in the form of divided materials such as granules, beads, pills, pellets, cylinders, trilobes, extrudates, spheres or other rounded shapes, or another manufactured configuration. Alternatively, the divided material may be in the form of irregularly shaped particles. Preferably at least a majority (*i.e.*, $>50\%$) of the particles or distinct structures have a maximum characteristic length (*i.e.*, longest dimension) of less than ten millimeters, preferably less than five millimeters.

[0086] The term "monolith" refers to any singular piece of material of continuous manufacture such as solid pieces of metal or metal oxide or foam materials or honeycomb structures. Two or more such catalyst monoliths may be stacked in the catalyst zone of the reactor if desired. In any case, the catalyst has sufficient porosity, or sufficiently low resistance to gas flow, to permit a stream of the reactant gas mixture to pass over the catalyst at a gas hourly space velocity (GHSV) of at least about $20,000 \text{ hr}^{-1}$, preferably at least $100,000 \text{ hr}^{-1}$, when the reactor is operated to recover elemental sulfur from an H_2S containing gas.

[0087] While the preferred embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the spirit and teachings of the invention. The embodiments described herein are exemplary only, and are not intended to be limiting. Many variations and modifications of the invention disclosed herein are possible and are within the scope of the invention. The discussion of a reference in the Description of Related Art is not an admission that it is prior art to the present invention, especially any reference that may have a publication date after the priority date of this application. The disclosures of all patents, patent applications and publications cited herein are hereby incorporated herein by reference, to the extent that they provide exemplary, procedural or other details supplementary to those set forth herein.